

Nitrogen and Tillage Effects on Irrigated Continuous Corn Yields

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ABSTRACT

A no-till (NT) production system has potential to reduce soil erosion, fossil fuel consumption, and greenhouse gas emissions compared with a conventional till (CT) system. Nitrogen fertilization (four to six N rates) and tillage system (CT and NT) effects on irrigated, continuous corn (*Zea mays* L.) yields were evaluated for 5 yr on a clay loam soil to determine the viability of the NT system and N needs for optimum yield. Corn in both NT and CT systems responded similarly to available N supply. Grain yields were significantly increased by N fertilization in both tillage systems, with a 16% higher average maximum yield in the CT than in the NT system. Grain yields were near maximum with an available N (soil + fertilizer N) level of 276 and 268 kg N ha⁻¹ in the CT and NT systems, respectively. Nitrogen fertilizer use efficiency (NFUE) averaged 43% over N rates and years for both systems. Total N required to produce 1 Mg of grain at maximum yield averaged 19 and 20 kg N Mg⁻¹ grain for the CT and NT systems, respectively. Corn residue increased with increasing N rate with no difference in residue production between tillage systems. The lower grain yield with NT probably resulted from the slow early spring development and delayed tasseling compared with the CT system as a result of cooler spring soil temperatures in the NT system. No-till, irrigated, continuous corn production has potential for replacing CT systems in the central Great Plains area, but with reduced yield potential. Current N fertilizer recommendations for CT corn based on yield goal may need to be modified for NT to account for the lower yield potential and slightly higher N requirement.

IRRIGATED FARMERS often use intensive tillage practices, particularly the moldboard plow, to manage the large quantity of crop residue returned to the soil surface when preparing a seedbed for the next crop. As a result of the numerous tillage operations, most of the crop residue is incorporated into the soil. With very little crop residue remaining on the soil surface, the soil is subject to wind and water erosion. Conversion from an intensively tilled irrigated crop production system to a conservation tillage system, like NT, would reduce the potential for soil erosion and loss of soil organic matter (Lal, 2004). Lal (2004) points out the need to use conservation tillage systems on croplands to enhance soil organic carbon (SOC) storage and reduce total greenhouse gas emissions from agricultural lands.

Limited information is available on use of NT systems on irrigated lands in the semiarid central Great Plains

(Cahoon et al., 1999; Sims et al., 1998). Data available from the more humid Western Corn Belt and eastern Nebraska suggest that NT systems may produce lower grain yields than CT systems (Wilhelm and Wortmann, 2004; Vetsch and Randall, 2002, 2004; Sims et al., 1998). Research suggests that cooler soil temperatures at planting time in NT systems delay early crop development and final yield (Sims et al., 1998; Swan et al., 1987). Sims et al. (1998) suggested that preplant tillage may be necessary to optimize grain yield when spring soil temperatures are cool on fine-textured soils. Sims et al. (1998) reported lower continuous corn yields with NT at low N rates compared with CT under sprinkler irrigation but equal yields at high N rates. Research from more humid areas suggests that the delay in early crop development with NT had no detrimental effect on final crop yield (Mehdi et al., 1999; Wolfe and Eckert, 1999).

Cahoon et al. (1999) reported higher yields and greater economic returns when using conservation tillage on irrigated continuous corn. Smart and Bradford (1999) also reported greater economic returns from NT than from a CT corn production system. Tolk et al. (1999) suggested that conservation tillage systems that maintain crop residues on the soil surface reduce evaporation and conserve water for crop growth and production, making more efficient use of the limited water supplies in the Great Plains. Todd et al. (1991) also demonstrated the benefit of surface mulch in reducing evapotranspiration in irrigated corn.

Halvorson et al. (2000) reported that plow tillage under furrow irrigation resulted in the loss of soil organic matter in the northern Great Plains, but the loss was less with a high level of N fertility. Under dryland production in eastern Colorado, Halvorson et al. (1999) showed that increasing N fertility level increased crop residue production, which resulted in greater soil organic matter. In an irrigated continuous corn production system, a large quantity of crop residue is produced. In a NT system, this residue is not incorporated with the soil, which slows the decomposition rate of the residue and release of residue N and other nutrients to the following crop. This may result in greater N requirements to attain equal grain yields for the NT system compared with the CT production system (Sims et al., 1998), at least for the first few years after converting to NT.

Farmers in the South Platte River Valley in north-eastern Colorado produce alfalfa (*Medicago sativa* L.), corn, winter wheat (*Triticum aestivum* L.), barley (*Hordeum distichon* L.), and dry bean (*Phaseolus vulgaris* L.) using predominantly intensive tillage (including the moldboard plow) to prepare a seedbed. Soil erosion

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Abbreviations: ARDEC, Agricultural Research Development and Education Center; CT, conventional till; NFUE, nitrogen fertilizer use efficiency; NT, no-till; SOC, soil organic carbon; WUE, water use efficiency.

due to wind and water is a serious problem in this irrigated area. Converting to a NT, irrigated production system will reduce soil erosion, reduce fossil fuel consumption through less tillage and fewer field operations, and potentially reduce greenhouse gas emissions through increased SOC sequestration.

We hypothesized that continuous corn yields under irrigation in the central Great Plains would be similar in both CT and NT production systems and that response to N fertilization would be similar. Our objectives were to determine: (i) the influence of tillage system (CT vs. NT) on irrigated corn yields, (ii) N fertilizer needs for optimizing corn grain yields in both tillage systems, and (iii) the influence of tillage system and N fertilization on crop residue production.

MATERIALS AND METHODS

This study was conducted on a Fort Collins clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research Development and Education Center (ARDEC) (40°39'6" N, 104°59'57" W; 1555 m above sea level) near Fort Collins, CO. The study was initiated in 1999 on a field that had previously been continuously cropped to corn for 6 yr using a CT system. The CT system used the following sequence of operations to prepare a seedbed for the next year's corn crop: in the fall, shredding of corn stalks was followed by tandem disking and then moldboard plowing to a depth of about 25 to 30 cm; in the spring, roller harrowing (two operations) and landplaning (two operations) were followed by cultivation, if needed, with a light-duty cultivator to reduce potential for wind erosion. In the NT system, corn was direct-planted into the previous year's corn stalks each spring without any other field operations for seedbed preparation, followed by application of herbicides for weed control and then harvest. The same planting, herbicide applications, and harvest operations were performed in the CT system, with no cultivation for weed control during the growing season. Triple superphosphate (0-46-0) was applied to the entire plot area before corn planting at 56 kg P ha⁻¹ in 1999 and 28 kg P ha⁻¹ in 2004. The soil had a pH of 7.6 (soil:0.01 M CaCl₂ solution ratio 1:2), organic matter content of 21 g kg⁻¹, electrical conductivity of 0.7 dS m⁻¹ (soil:water ratio 1:1), sodium bicarbonate extractable P content of 17 g kg⁻¹, and a clay and silt contents of 33 and 27%, respectively, in the 0- to 15-cm depth.

Six N rates (0, 34, 67, 101, 134, and 202 kg N ha⁻¹ referred to as N1, N2, N3, N4, N5, and N6, respectively) were established in 2000 in the NT system. In the CT system, only the N1, N3, N5, and N6 treatments were present in 2000 and 2001. In 2002, the N2 treatment was added, and in 2003 the N4 treatment was added to the CT system when plot area embedded within the existing plots but used for another experiment became available. Due to only a minimal grain yield response to N fertilization at the N6 rate in 2000, the fertilizer N rate was reduced to 168 kg N ha⁻¹ in 2001, increased back to 202 kg N ha⁻¹ in 2002, and then increased to 224 kg N ha⁻¹ in 2003 and 2004 due to obvious N shortage in the NT system with each additional corn crop. The same rate of N was applied to the same plots each year with the exception of the N6 treatment. The N source was UAN (32-0-0), which was applied with a liquid fertilizer applicator that banded the N about 5 cm below the soil surface in bands spaced 33 cm apart (parallel to the corn row, but at varying distance from the corn row) the day before corn planting. Starter P and K fertilizer was applied directly with the seed at planting except in 2001. The experi-

mental design was a split-plot, randomized complete block with tillage main plots (CT, 62 by 130 m; NT, 21 by 137 m) and N rate as subplots (CT, 10.7 by 21.6 m; NT, 10.7 by 15.2 m) within tillage treatment with three replications.

Corn hybrid Pioneer Brand 38B22 Bt LL was planted with a 76-cm row spacing on 27 Apr. 2000, DeKalb DK440 RR/YG on 30 Apr. 2001, Pioneer Brand 37H26 LL on 24 Apr. 2002, DeKalb DKC44-46 RR/YGCB on 28 Apr. 2003, and Pioneer Brand 38P04 LL on 27 Apr. 2004 in the plot area. Planting rates were approximately 84 000 seeds ha⁻¹ in 2000, 2003, and 2004; 91 000 seeds ha⁻¹ in 2001; and 96 000 seeds ha⁻¹ in 2002. Seeding rates were the same for both tillage systems. The corn planter was equipped with residue managers or trash whippers to facilitate planting in the NT system. All corn hybrids had about a 94-d relative maturity. Corn hybrid was changed from year to year to allow herbicide rotation. Plant populations were estimated each year by counting the number of plants in two 7.6-m-long rows that were used for grain harvest. Herbicides were applied for weed control, and the plots were essentially weed free during the study period.

The corn was sprinkler-irrigated with a linear-move system as needed [determined weekly by the feel method (Klocke and Fischbach, 1998)] during the growing season. Irrigation amounts each month are shown in Table 1. The irrigation water contained an average of 2.8 mg NO₃-N L⁻¹ in 2002, 3.6 mg NO₃-N L⁻¹ in 2003, and 2.1 mg NO₃-N L⁻¹ in 2004. In 2000 and 2001, N level in the water was not monitored but was assumed to be similar to that in 2002–2004. The total N contribution from the irrigation water to the plot area was estimated to total about 12 kg N ha⁻¹ in 2000, 12 kg N ha⁻¹ on CT plots and 10 kg N ha⁻¹ on the NT plots in 2001, 14 kg N ha⁻¹ in 2002, 15 kg N ha⁻¹ in 2003, and 8 kg N ha⁻¹ in 2004 during irrigation of the corn with a very small amount (not measured) of irrigation water runoff from the CT plot area, but none from the NT system.

Annual precipitation at ARDEC for the study period is shown in Table 1. Annual precipitation for the site for the May through September corn growing season varied from a low of 122 mm in 2001 to a high of 181 mm in 2004. All corn growing seasons had below-average precipitation. Due to severe drought conditions (Table 1) from 2000 through 2003, irrigation water availability was questionable in 2003 and 2004; therefore, corn populations in the plot area were reduced in case irrigation water became unavailable late in the growing season.

Crop residue cover on the soil surface was estimated each spring just before planting using the line-transect method. Soil NO₃-N levels in the 0- to 180-cm profile were monitored from 2000 through 2004 and were measured before spring fertilization and after corn harvest. One soil core sample was collected from near the center of each plot each spring (0- to 180-cm profile) before planting and from the edge of the corn row after harvest each crop year in increments of 0 to 7.6, 7.6 to 15.2, and 15.2 to 30.4 cm and then 30.4-cm increments to a depth of 180 cm for determination of gravimetric soil water and soil NO₃-N content. Soil NO₃-N was determined by Cd reduction using a continuous-flow analyzer (Lachat Quick-Chem FIA+8000 Series,¹ Lachat Instruments, 2001) after extraction with 1 M KCl (soil:solution ratio 1:5). Soil bulk density was determined on the soil cores from the 0- to 30-cm depths from each plot during the fall sampling. Soil bulk density was determined for the 30- to 180-cm soil depths of each replication and an average value calculated for the entire plot area.

¹ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA-ARS.

Table 1. Monthly precipitation received and irrigation water applied to the conventional till (CT) and no-till (NT) plots.

Month	Precipitation							Irrigation water applied					
	1999	2000	2001	2002	2003	2004	Avg.	2000 CT	2000 NT	2001	2002	2003	2004
	mm												
Jan.	6	1	5	8	1	3	4	0	0	0	0	0	0
Feb.	0	2	5	1	8	3	3	0	0	0	0	0	0
Mar.	9	5	5	8	26	4	9	0	0	0	0	0	0
Apr.	121	12	21	4	10	26	32	0	0	0	25	0	48
May	53	32	60	46	92	27	52	57	51	19	37	32	38
June	56	21	11	17	36	44	31	116	50	127	104	51	44
July	41	14	31	21	4	18	21	157	157	160	192	165	108
Aug.	57	10	8	26	27	35	27	84	84	178	120	151	110
Sept.	14	44	17	28	5	57	27	0	0	0	27	13	13
Oct.	2	13	6	9	1	19	8	0	0	0	0	0	0
Nov.	5	6	11	9	6	5	7	0	0	0	0	0	0
Dec.	0	2	0	0	4	2	1	0	0	0	0	0	0
Total	365	163	179	178	218	242	224	414	342	484	505	411	362
Total (May–Sept.)	222	122	126	139	164	181	159						

The soil bulk density was used to calculate soil $\text{NO}_3\text{-N}$ mass on an area basis.

The grain and crop residue samples collected for N analysis were ground to pass a 150- μm screen and analyzed for N content using a Carlo Erba C/N analyzer (Haake Buchler Instruments, Inc., Saddle Brook, NJ).¹ Nitrogen fertilizer use efficiency (NFUE) by the corn crop was estimated by dividing the N uptake in corn grain minus the N uptake in the no-fertilizer-N treatment (check) divided by the quantity of N applied. This fraction was multiplied by 100 to obtain percentage NFUE.

Corn grain yields were generally determined in late October each year by hand-harvesting the ears from a 11.6-m² area of each plot. The ears were shelled with a corn sheller to determine grain and cob weights. Grain yields were measured when the corn was at physiological maturity at about 160 to 170 g kg⁻¹ water content, and final grain yield was expressed at 155 g kg⁻¹ water content. Aboveground corn biomass was determined in September each year by hand-harvesting 15 whole corn plants from a 1.5 m² or larger area from each plot. The plants were separated into grain, cobs, and stover for mass determination.

Analyses of variance were performed using Analytical Software¹ Statistix8 program (Analytical Software, 2003) to determine treatment effects. All statistical comparisons were made at the $\alpha = 0.05$ probability level unless otherwise stated using the least significant difference method for mean separation. If the analysis of variance indicated a significant F value for N rate, a linear or quadratic function was fit to the N response data using regression functions present in the graphics program (SigmaPlot version 9.0, SPSS Inc., Chicago, IL¹).

RESULTS AND DISCUSSION

Crop Residue Cover on Soil Surface

The percentage of crop residue cover on the soil surface each spring at corn planting is shown in Table 2 for each of the tillage treatments. Averaged over years and N treatments, residue cover on the soil surface was significantly greater in the NT system (89%) than in the CT system (14%). Residue cover did not vary with N rate in the NT system but varied slightly with N rate in the CT system (significant N rate \times year interaction). This interaction resulted due to the lowest N rate having the lowest amount of residue cover in 2003 and the greatest level in 2004. The CT system had an average of 84% less surface residue cover than the NT system

averaged over the 5 yr. Residue cover in the NT system increased significantly from 2000 to 2003. The level of surface residue cover in the NT system was sufficient to visually reduce soil erosion by wind and water during the study period when compared with the CT system.

Grain Yield

Corn grain yields increased each year with increasing N fertilizer rates in both tillage systems with a significant tillage \times N rate \times year interaction (Fig. 1). Grain yields were significantly greater in CT than in the NT system in all years with the response to increasing N rate being more linear (except for 2000) in the NT system than in the CT system. Colder soil temperatures (Liu et al., 2005) in the NT system compared with the CT system delayed corn seedling emergence and development in early May each year, with the corn in the CT system tasseling and completing pollination 5 to 8 d earlier than the NT corn. Established corn plant populations were significantly greater in the CT system in 2000 and 2001 (82 400 and 90 300 plants ha⁻¹, respectively) than in the NT system (73 800 and 86 300 plants ha⁻¹, respectively). Plant populations between tillage treatments were not significantly different in 2002, 2003, and 2004 with respective plant populations of 93 700, 80 600, and 82 000 plants ha⁻¹ for CT system and 96 000, 76 000, and 81 300 plants ha⁻¹ for the NT system. Plant populations were generally slightly greater in the CT than in the NT system,

Table 2. Soil residue cover at planting each year for each N treatment in conventional till (CT) and no-till (NT) continuous corn plots from 2000 through 2004.

N treatment	CT system					NT system				
	2000	2001	2002	2003	2004	2000	2001	2002	2003	2004
	%									
N1	21b†	11a	2a	13c	16a	80a	88a	86a	94a	92a
N2			3a	22b	16a	75a	85a	84a	96a	92a
N3	18b	12a	2a	29a	11b	78a	87a	86a	99a	99a
N4				29a	10b	77a	87a	91a	99a	96a
N5	19b	13a	3a	25ab	10b	76a	92a	91a	99a	96a
N6	28a	11a	3a	26ab	12b	76a	90a	91a	98a	97a
Average	21a‡	12b	2c	24a	13b	77c	88b	88b	98a	95a

† Values within a year column of N rates followed by the same letter are not significantly different at $\alpha = 0.05$.

‡ Average values within a row for each tillage system followed by the same letter are not significantly different at $\alpha = 0.05$.

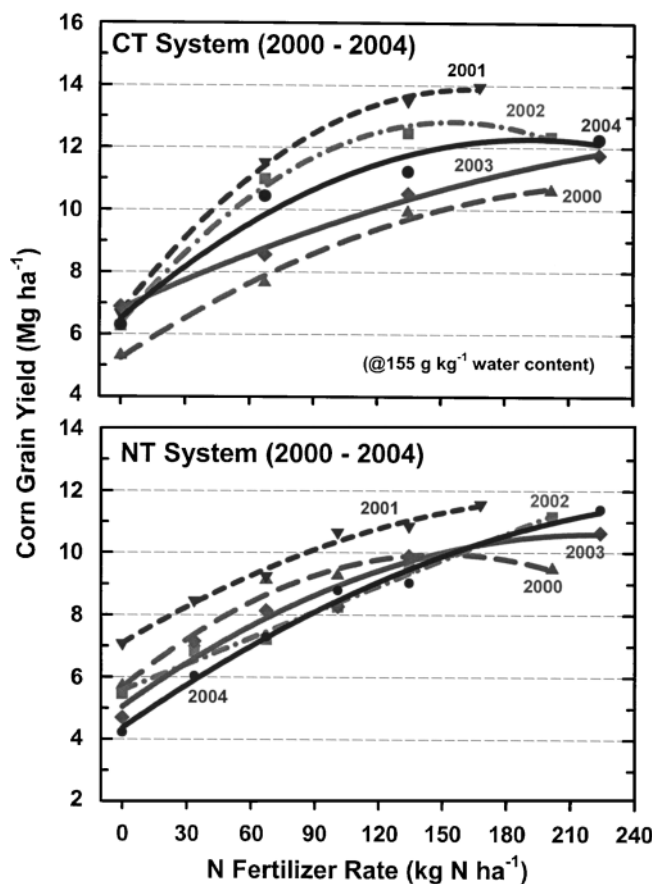


Fig. 1. Corn grain yields in conventional till (CT) and no-till (NT) treatments as a function of N fertilizer application rate for five crop years at Fort Collins, CO.

which may have contributed somewhat to the yield differences between tillage treatments. However, in 2002, when NT had a slightly higher plant population than CT, and in 2004, when plant populations were nearly the same, yields were still lower in the NT system than in the CT system. Thus, the effect of plant stand on yield was not obvious. Residual soil $\text{NO}_3\text{-N}$ tended to be

Table 3. Spring soil $\text{NO}_3\text{-N}$ levels for each N treatment in conventional till (CT) and no-till (NT) plots from 2000 through 2004.

N treatment	CT system					NT system				
	2000	2001	2002	2003	2004	2000	2001	2002	2003	2004
kg N ha ⁻¹										
0- to 90-cm soil depth										
N1	27	37	28	35	28	32	45	30	16	14
N2	-	-	61	47	30	21	47	30	15	15
N3	34	43	34	35	35	33	49	32	17	16
N4	-	-	-	35	30	37	52	30	21	19
N5	42	42	37	38	36	34	57	48	23	25
N6	44	83	68	121	102	32	67	54	30	34
LSD _{0.05}	4	11	17	34	37	NS	NS	17	10	7
0- to 180-cm soil depth										
N1	34	58	41	43	47	57	79	44	23	21
N2	-	-	79	63	54	32	81	46	23	24
N3	44	73	43	43	58	51	84	49	30	27
N4	-	-	-	43	58	50	89	46	40	33
N5	52	69	53	48	64	52	99	85	49	42
N6	57	119	94	180	166	49	104	88	74	59
LSD _{0.05}	11	16	19	36	49	NS	NS	24	17	14

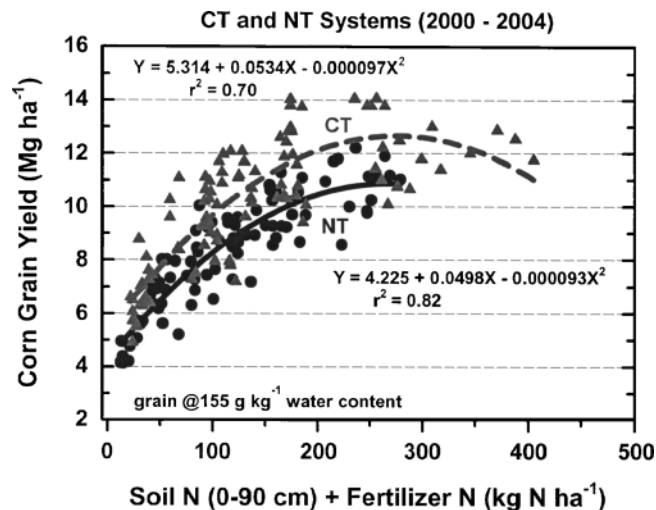


Fig. 2. Corn grain yields in conventional till (CT) and no-till (NT) treatments as a function of plant available N [soil N (0-90 cm depth) plus fertilizer N applied] for five crop years at Fort Collins, CO.

slightly higher in the CT system at the higher N rates than in the NT system (Table 3), thus providing a higher level of available N at the same N fertilizer rate in the CT system than in the NT system and thus contributing to a lower yield potential in the NT system. Analysis of the corn ear data obtained at biomass sampling from 2001 to

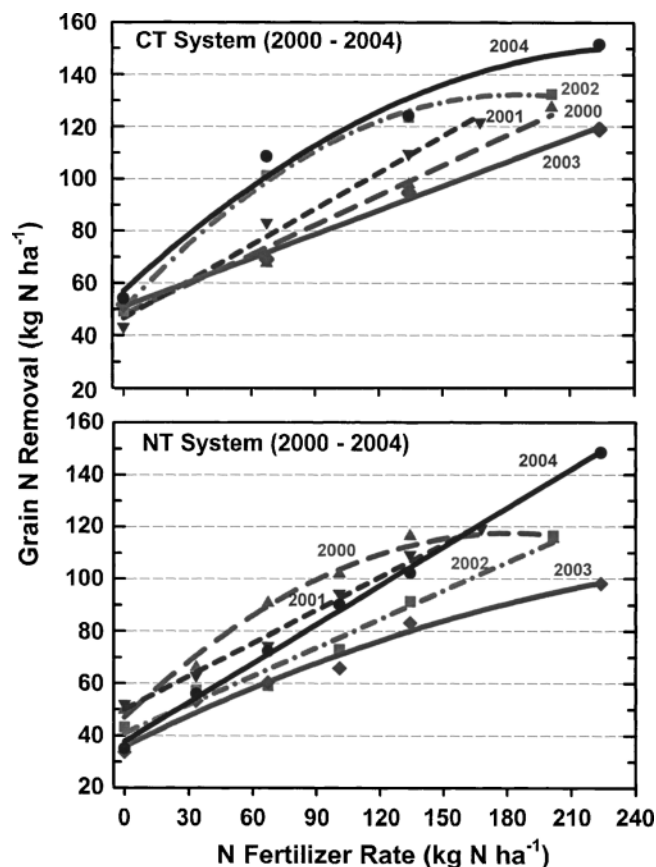


Fig. 3. Total N removed in grain from plot area in conventional till (CT) and no-till (NT) systems with increasing N rate each crop year from 2000 through 2004.

2004 indicates that cob size was similar between the CT and NT systems. Averaged over years and N rates, there was no significant difference in oven dry cob weight between the CT system (1260 kg ha⁻¹) and the NT system (1280 kg ha⁻¹) with no significant tillage × N rate interaction. Cob weight increased with increasing N rate 930, 1190, 1410, and 1550 kg ha⁻¹ for the N1, N3, N5, and N6 treatments, respectively. Averaged over years (2001–2004), the NT system had 27, 25, 23, and 15% less grain for the N1, N3, N5, and N6 treatments, respectively, than in the CT system. Thus, as available N increased, differences in grain yield between the tillage systems decreased. Other researchers have reported lower corn grain yields with NT than with CT systems (Sims et al., 1998; Swan et al., 1987). Thus, the slow spring plant development and delayed tasseling time with NT compared with CT resulted in less grain production at the end of the season. On an economic basis (not considered in this paper), the lower grain yield with NT is expected to be partially offset by increased production costs with CT, particularly with the large number of field operations used to prepare a seedbed.

Expressing corn grain yield as a function of available N [soil NO₃-N (0- to 90-cm depth) plus fertilizer N applied] for all 5 yr combined (Fig. 2) shows that the response (slopes) to available N is similar for both tillage systems

but yields (y axis intercept) were greater in the CT system. Based on the regression equations, the amount of total available N needed to maximize grain yield was 276 and 268 kg N ha⁻¹ for the CT and NT systems, respectively. Therefore, maximum yield in both systems occurred at similar available N levels. Halvorson et al. (2005) reported maximum yields in furrow-irrigated continuous corn occurred at 265 kg N ha⁻¹ of available N (soil + fertilizer N). This would indicate that N fertilizer recommendations used for CT corn production systems (Bauder and Waskom, 2003) can be used for a NT corn production system provided that a correction is made for yield goal and/or N requirement per unit of yield. Based on yields from all 5 yr, the CT system at maximum yield potential had a 16% yield advantage (1781 kg ha⁻¹) over the NT system.

Water use efficiency (WUE), defined as kilograms of grain per hectare produced per millimeter of available growing season water [precipitation + irrigation water applied + soil water used (0- to 180-cm depth)], was increased by N application in this study. Combining data from all plots over the 5-yr period, WUE increased curvilinearly with increasing level of available N (soil + fertilizer N) in both the CT and NT systems (data not shown). In the NT system, a significant relationship between WUE and available N (AN) was observed as expressed by the

Table 4. Coefficients for the regression equations ($Y = a + bX$ or $Y = a + bX + cX^2$) in Fig. 1, 3, 4, 6, 7, and 8 with the Y factor indicated for each figure as a function of fertilizer N rate (X). CT = conventional till and NT = no-till.

Year	CT system				NT system			
	a	b	c	r ²	a	b	c	r ²
Figure 1: grain yield								
	Mg ha ⁻¹							
2000	5.233	0.0456	-0.00009	0.99	5.668	0.0570	-0.00019	0.97
2001	6.709	0.0881	-0.00027	0.99	7.095	0.0416	-0.00009	0.99
2002	6.358	0.0831	-0.00027	0.99	5.570	0.0279		0.99
2003	6.817	0.0319	-0.00004	0.99	5.046	0.0498	-0.00011	0.96
2004	6.507	0.0599	-0.00016	0.97	4.360	0.0484	-0.00008	0.99
Figure 3: grain N removal								
	kg N ha ⁻¹							
2000	48.05	0.3793		0.98	46.91	0.7779	-0.00214	0.99
2001	46.67	0.4630		0.99	50.07	0.4205		0.99
2002	50.02	0.8863	-0.00239	0.99	40.89	0.3631		0.97
2003	50.98	0.3072		0.99	35.76	0.4055	-0.00056	0.98
2004	56.92	0.7551	-0.00152	0.98	37.68	0.4966		0.99
Figure 4: N removal in corn grain								
	kg N Mg ⁻¹ grain							
2000	9.543	0.0116		0.51	9.257	0.0201		0.94
2001	6.767	0.0140		0.99	7.381	0.0211		0.95
2002	8.547	0.0143		0.98	8.194	0.0136		0.93
2003	7.848	0.0124		0.99	7.422	0.0102		0.96
2004	9.381	0.0171		0.96	8.904	0.0219		0.99
Figure 6: corn residue N								
	kg N ha ⁻¹							
2000	45.10	0.2094		0.95	31.42	0.7294	-0.00272	0.89
2001	28.05	0.2242		0.82	43.38	0.2842		0.97
2002	25.73	0.1743		0.98	24.45	0.1666		0.98
2003	19.81	0.1556		0.97	15.02	0.1087		0.96
2004	19.79	0.1641		0.99	15.96	0.1825		0.92
Figure 7: total (grain + residue) N uptake								
	kg N ha ⁻¹							
2000	93.19	0.5885		0.99	78.32	1.5078	-0.00487	0.98
2001	74.75	0.6871		0.99	93.46	0.7046		0.99
2002	74.12	1.1338	-0.00275	0.99	65.35	0.5308		0.98
2003	70.60	0.4628		0.99	54.82	0.3865		0.98
2004	85.72	0.5748		0.95	53.65	0.6788		0.99
Figure 8: total N requirement								
	kg N Mg ⁻¹ grain							
2000	20.17	0.0122		0.45	18.41	0.0297		0.64
2001	12.57	0.0169		0.49	15.45	0.0355		0.87
2002	13.75	0.0221		0.99	14.56	0.0191		0.93
2003	12.41	0.0218		0.97	11.73	0.0143		0.71
2004	13.85	0.0279		0.99	14.51	0.0292		0.87

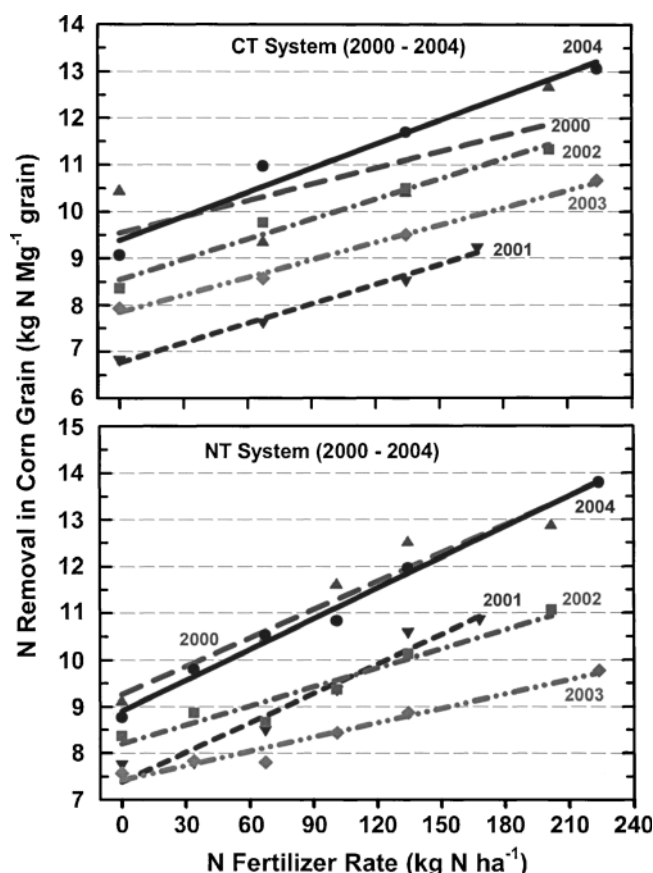


Fig. 4. Amount of N removed in 1 Mg of grain as a function of N rate and year for the conventional till (CT) and no-till (NT) systems.

regression equation $WUE = 7.23 + 0.090AN - 0.00019AN^2$ with an r^2 of 0.52. Likewise, in the CT system, the regression relationship between WUE and AN was $WUE = 10.00 + 0.087AN - 0.00015AN^2$ with an r^2 of 0.62. Water use efficiency was maximized (23 kg grain ha^{-1} mm $^{-1}$ water) in the CT system at an available N level of 290 kg N ha^{-1} and in the NT system (18 kg grain ha^{-1} mm $^{-1}$ water) at 237 kg N ha^{-1} . Al-Kaisi and Yin (2003) reported similar increases in WUE with N application in eastern Colorado on a sandy soil.

Grain Nitrogen Removal

Grain N removal increased in both tillage systems with increasing N rate with differences between years (signifi-

cant tillage \times N treatment \times year interaction) similar to grain yield (Fig. 3). Because of the significant three-way interaction, the response of grain N removal to N fertilizer rate for each tillage treatment and year is presented separately in Fig. 3. Table 4 reports the regression coefficients for each year's data. Grain N removal was 17.5% greater in the CT system (94 kg N ha^{-1}) than the NT system (80 kg N ha^{-1}) when averaged over N rates and 5 yr. This reflects the higher grain yields in the CT system than in the NT system. Averaged over tillage system and years, grain N removal was in the order $N_6 > N_5 > N_3 > N_1$ or 125, 105, 79, and 46 kg N ha^{-1} . The tillage \times N rate interaction was not significant. The amount of N removed in each megagram of grain as a function of tillage system and N rate is shown in Fig. 4. The amount of N removed with each megagram of grain (oven dry basis) increased with increasing N rate (Fig. 4) as did grain yield (Fig. 1). At the higher N rates, the amount of N in each megagram of grain was similar to that reported by Heckman et al. (2003) and Halvorson et al. (2005).

Nitrogen fertilizer use efficiency tended to decrease with increasing N rate (Table 5) with a significant tillage \times N rate \times year interaction. Therefore, tillage system and years were analyzed individually in Table 5. The tillage \times N rate interaction was not significant. The NFUE varied from year to year in both tillage systems. Within the CT system, NFUE decreased significantly with increasing N rate in 2002 and 2004 but was not significantly different between N rates in 2001 and 2003 or the 5-yr average. Within the NT system, N rate had no significant effect on NFUE although the trend was for NFUE to decrease with increasing N rate. The 5-yr average NFUE for each tillage treatment was similar for N_3 , N_5 , and N_6 treatments with respective NFUE values of 48, 42, and 38% for CT and 43, 43, and 38% for the NT system.

Corn Residue

Corn residue (leaves, stalks, and cobs) production increased with increasing N rate (Fig. 5) each year, but the total amount of residue varied from year to year in both tillage systems. Averaged over tillage and N rates, yearly residue production was in the order 2001 $>$ 2002 $>$ 2004 = 2000 $>$ 2003 or 10 150, 8080, 7370, 7060, and 6450 kg ha^{-1} , respectively, similar to grain yield. The N rate \times year interaction was not significant; therefore, residue production as a function of N rate in both tillage

Table 5. Nitrogen fertilizer use efficiency (NFUE) based on grain N removal each year for each N treatment in conventional till (CT) and no-till (NT) continuous corn plots from 2000 through 2004.

N rate	CT system						NT system					
	2000	2001	2002	2003	2004	5-yr avg.	2000	2001	2002	2003	2004	5-yr avg.
NFUE, %												
N2							49a	32a	42a	58a	62a	49a
N3	18b†	56a	72a	23a	72a‡	48a	61a	33a	24a	40a	56a	43a
N4							52a	42a	30a	32a	55a	42a
N5	32a	48a	53b	34a	48b	42a	50a	43a	36a	37a	50a	43a
N6	33a	45a	40b	28a	41b	38a	33a	40a	36a	29a	51a	38a
Avg.	28b§	50a	55a	27b	53a	43	49a	38b	34b	39b	55a	43

† Values within a year column of N rates followed by the same letter are not significantly different at $\alpha = 0.05$.

‡ 2004 significance at $\alpha = 0.10$.

§ Average values within a row for each tillage system followed by the same letter are not significantly different at $\alpha = 0.05$.

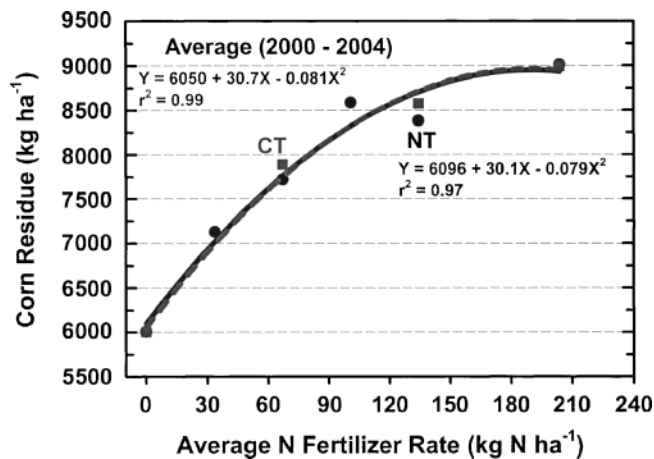


Fig. 5. Corn residue production for conventional till (CT) and no-till (NT) systems as a function of N rate averaged over years from 2000 through 2004.

systems is shown in Fig. 5. Residue quantity produced each year was similar for both tillage systems in contrast to grain yield. Averaged over N rate and years, residue production averaged 7870 and 7780 kg ha⁻¹ for the CT and NT systems, respectively. Therefore, the NT system had the same size plant as the CT system but produced less grain than the CT system.

The amount of N in the corn residue at harvest increased with increasing N rate in both tillage systems

(Fig. 6). Thus, the higher N rates had more N cycling back to the soil with the residue than the lower N rates. This probably contributed to a slightly higher level of available N to the corn crop in the CT system (Table 3) where residues were incorporated into the soil and subject to microbial decomposition than in the NT system (Paul and Clark, 1989). The residue in the NT system stayed on the soil surface and decomposed much slower than in the CT system.

The increasing amount of corn residue returned to the soil with increasing N rate is expected to contribute to differences in SOC among N rates with time. The highest N rate contributed about 3000 kg ha⁻¹ more corn residue than the zero-N rate in both tillage treatments (Fig. 5). Averaging the corn residue data only from 2003 and 2004 over tillage treatments and years resulted in a linear increase in residue production, with 1 kg fertilizer N ha⁻¹ resulting in the production of 12.8 kg ha⁻¹ of residue.

Total Nitrogen Uptake and Total Nitrogen Requirements

The total N uptake (grain + residue) by each corn crop is shown in Fig. 7. Total N uptake increased with increasing N rate and biomass production each year. Except for 2003, total N uptake was similar each year in the CT system; however, it varied greatly with years in the NT system. The increases were generally linear each year for

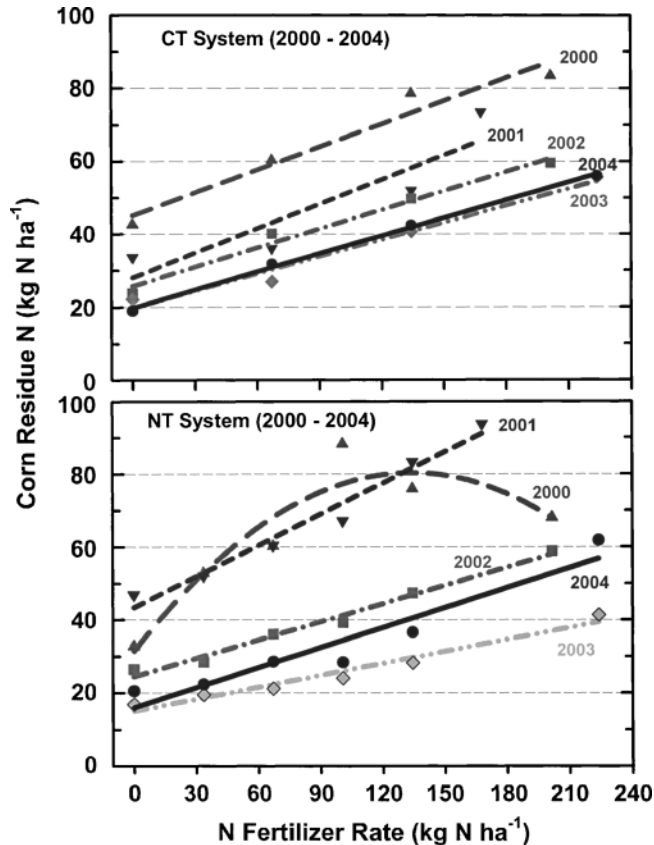


Fig. 6. Corn residue N uptake as a function of N rate and year for the conventional till (CT) and no-till (NT) systems.

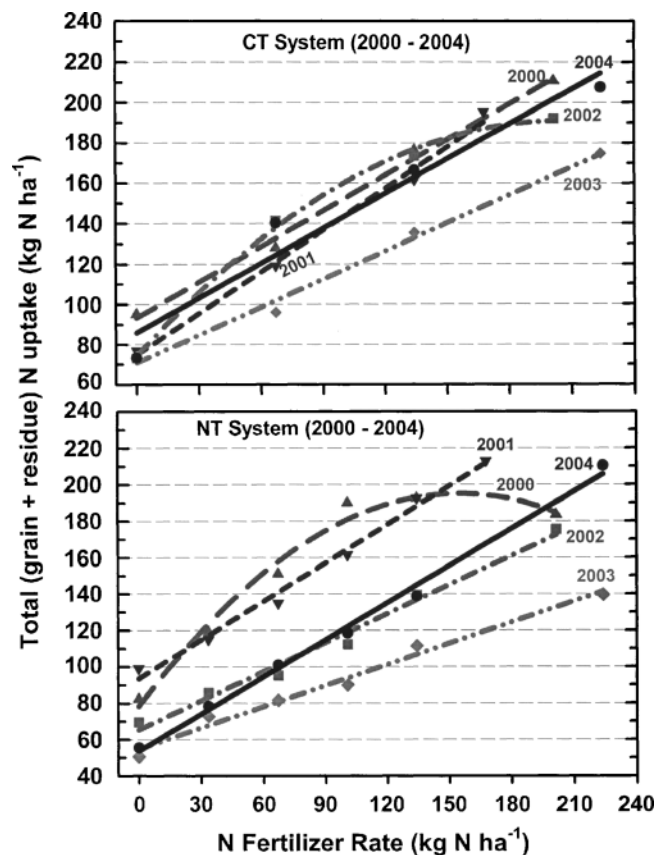


Fig. 7. Total N uptake (grain N + residue N) as a function of N rate and year for the conventional till (CT) and no-till (NT) systems.

both tillage systems except for 2002 in CT and 2000 in NT. The tillage \times N rate \times year interaction was significant, so each tillage system was analyzed separately. The tillage \times N rate interaction was not significant. Averaged over years and N rates, the CT system resulted in greater N uptake (141 kg N ha^{-1}) compared with the NT system (131 kg N ha^{-1}). Averaged over tillage treatment and N rates, total N uptake was greater in 2000 (152 kg N ha^{-1}) and 2001 (149 kg N ha^{-1}) than in 2004 (137 kg N ha^{-1}) and 2002 (132 kg N ha^{-1}), and uptake in these years was greater than in 2003 (108 kg N ha^{-1}).

The total amount of N required to produce 1 Mg of grain (oven dry basis) increased with increasing N rate (Fig. 8) and increasing grain yield (Fig. 1). An average total N requirement of $21.0 \text{ kg N Mg}^{-1}$ grain was required to produce the 2000 corn crop, $16.7 \text{ kg N Mg}^{-1}$ grain in 2001, $16.3 \text{ kg N Mg}^{-1}$ grain in 2002, $14.1 \text{ kg N Mg}^{-1}$ grain in 2003, and 17.4 in 2004 with a 5-yr average of $17.1 \text{ kg N Mg}^{-1}$ grain when averaged over tillage and N rates. The 5-yr average total N requirement to produce 1 Mg of grain at near-maximum yield potential was 19.2 and $20.1 \text{ kg N Mg}^{-1}$ grain for the CT and NT systems, respectively. The total N requirement values from this study at maximum yield were in the range of total N needs of irrigated corn of 19.6 to $21.4 \text{ kg N Mg}^{-1}$ grain yield often reported by those making N fertilizer recommendations for grain corn (Bauder and Waskom, 2003; Karlen et al., 1998).

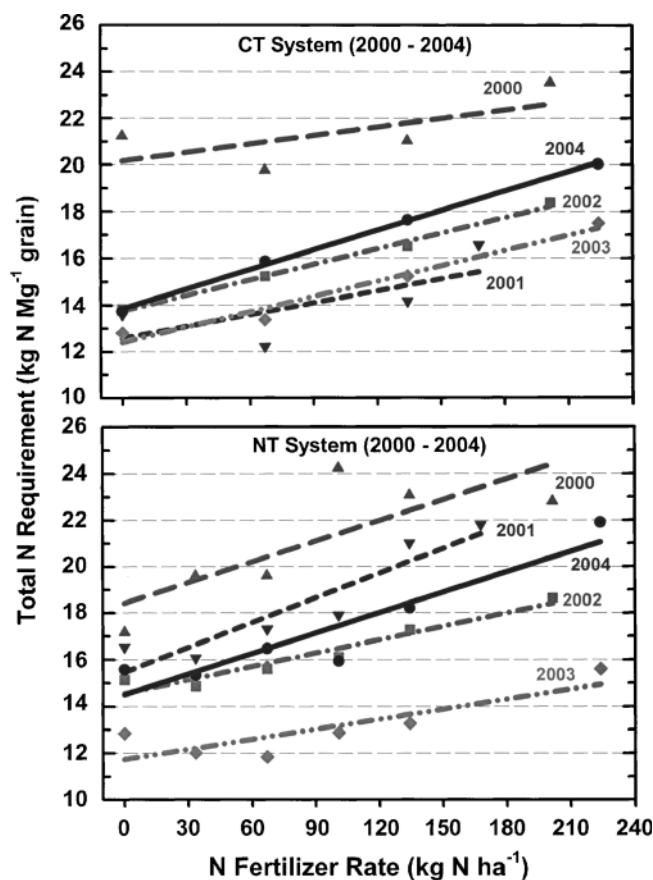


Fig. 8. Total N requirement to produce 1 Mg of grain as a function of N rate and year for the conventional till (CT) and no-till (NT) systems.

Soil Nitrate

Soil $\text{NO}_3\text{-N}$ levels just before planting each spring were similar between both tillage systems in 2000 through 2002 at both the 0- to 90- and 0- to 180-cm soil depths (Table 3). In 2003 and 2004, soil $\text{NO}_3\text{-N}$ levels were lower in the NT system than in the CT system, particularly at the highest N rate. The highest N rate was increased from 202 kg N ha^{-1} in 2002 to 224 kg N ha^{-1} in 2003 and 2004. A large increase in residual soil $\text{NO}_3\text{-N}$ was observed in the CT system at the highest N rate compared with a decrease in the NT system, indicating that excess N was probably being applied to the CT system and that the NT system probably needed a slightly higher rate of N. The lower level of available soil N could account for some of the grain yield difference between the CT and NT systems (Fig. 2).

SUMMARY

Corn grain yields were significantly increased by N fertilization each year in both tillage systems, with 16% higher yield in the CT than in the NT system at maximum yield. Grain yields were near maximum with an available N (soil + fertilizer N) level of 276 and 268 kg N ha^{-1} in the CT and NT systems, respectively. Nitrogen fertilizer use efficiency (NFUE) based on grain N removal tended to decrease, but not always significantly, with increasing N rate in both systems, averaging 43% over N rates and years for both systems. Total N required to produce 1 Mg of grain at maximum yield averaged 19 and 20 kg N Mg^{-1} grain for the CT and NT systems, respectively. Corn residue returned to the soil increased with increasing N rate with no difference in residue production between tillage systems. Therefore, the NT system had the same size plant for grain production as in the CT system. The lower grain yield with NT probably resulted from the slow early-spring development and delayed tasseling compared with the CT system as a result of cooler spring soil temperatures in the NT system. Addition of N fertilizer increased the level of soil $\text{NO}_3\text{-N}$ throughout the 0- to 180-cm profile at the highest N application rate (224 kg N ha^{-1}) in the CT system during 2003 and 2004 but not in the NT system.

This work shows that NT, irrigated, continuous corn production has potential for replacing CT production systems in the central Great Plains area, but some type of reduced tillage, such as strip-tillage (Licht and Al-Kaisi, 2005; Vetsch and Randall, 2002), may be required to improve grain yields in the conservation tillage system. The study shows that corn in the NT system responded similarly to available N supply compared to the CT system. Current N fertilizer recommendations for CT corn based on yield goal may need to be modified for NT to account for the lower yield potential and slightly higher N need with NT.

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